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# Optimal sizing of a standalone photovoltaic system for remote housing electrification using numerical algorithm and improved system models

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ABSTRACT

This paper presents a size optimization method of the energy sources in a standalone photovoltaic system. The proposed technique implies improved photovoltaic array model, dynamic battery model, and accurate objective function as well as a fast simulation algorithm. The loss of load probability (LLP) is used to define the availability of the system. Different system's configurations with different availability levels are generated using the proposed algorithm. These configurations are evaluated based on system availability and cost. Hourly meteorological and load demand data are utilized in this research. A design example is done to show the application of the proposed method considering the weather profile of Malaysia. The result shows that the optimal sizing ratio of the photovoltaic array ($C_A$) is 1.184, while the sizing ratio for storage battery ($C_B$) is 0.613. In addition, the levelized cost of energy (LCE) for the unit generated of energy by the proposed system is 0.447 $/kWh.

## 1. Introduction

The rapid depletion of fossil fuel sources worldwide has presupposed an urgent search for alternative sources to cover the present day demand. The energy demand is increasing and the conventional energy sources cannot cover this demand entirely due to their limited supplies. In addition to that, conventional energy sources have negative impacts on the environment. Based on that, renewable and sustainable energy sources such as photovoltaics (PV) have attracted the energy sector to be considered as power generating sources as they are environment friendly and secure [1]. However, PV power systems must be designed optimally so as to provide a feasible system that covers the desired load demand at a defined level of availability. PV systems size is mainly depending on meteorological data such as solar radiation and ambient temperature. This is due to the fact that the output of these systems strongly depends on the availability of solar radiation and ambient temperature [2].

Currently, many research works are carried out to develop size optimization techniques for standalone PV system so that number of PV modules, and the capacity of storage units are optimally selected. System's size optimization is mainly conducted through bi-objective techno-economic optimization problem that is formulated based on the best trade-off between system's cost and availability [3]. Different sizing methods have been proposed in previous research works to obtain an optimum size of standalone PV system. These methods can be classified as intuitive methods [4–6], numerical methods [7–13], analytical methods [14–16]. Intuitive methods are defined as the sizing approaches that are based on simplified calculations without establishing quantitative relationship between the different system components or taking into consideration the uncertainty nature of the energy source [17]. The major disadvantage of these methods that they may lead to an over/under sizing of the system which will result an unreliable and feasible system [18]. On the other hand, in the analytical methods, the components of the PV system are characterized by mathematical models in terms of system's availability. The availability of the system consequently can be estimated for different system's configurations. The main advantage of this method that the sizing calculations are very simple while the disadvantage is the difficulty of estimating the coefficients of these mathematical models and

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the dependency of these models on location [19].

Finally, numerical methods imply system simulation that is developed based on hourly or daily time period. This method can be divided into two approaches namely stochastic approaches and deterministic approaches. In stochastic approaches, hourly (or smaller) solar radiation and load demand data are considered in the simulation. Meanwhile, in the deterministic approaches, average daily solar radiation and load demand data are used. This method is accurate and the availability of the system can be applied in a quantitative way [19]. System's availability can be described by many statistical terms such as loss of power supply probability (LPSP), loss of load expected (LOLE), equivalent loss factor (ELF), total Energy loss (TEL), battery state of charge (SOC), and level of autonomy (LA), loss of load probability (LLP) [20]. LLP can be defined as the ratio of the energy produced by the PV system to the unmet load demand for a time period [21].

In general, there are four aspects of the numerical methods that must be considered namely; input data, system's models; si - ulation methods and formulated objective function. The input data for numerical method are divided into two parts; system specifications, and meteorological and load demand data. The nature of the meteorological and load demand data strongly affects the sizing results. Some of authors used monthly averages meteorological data[9,10,29], while others used daily averages meteorological data [10,14]. However, the use of monthly and daily averages may affect the accuracy of the results as the uncertainty nature of these data is not considered. Therefore, such an analysis must be done using hourly meteorological data in order to get accurate sizing results. On the other hand, the accuracy of the utilized system's models such as PV array model and the storage battery model strongly affect the optimization result accuracy as well. Models with many simplifications may not reflect an accurate performance of the system and consequently inaccurate availability index of the system. In general, most of the authors use simple PV modes such as empirical models [8,10], regression models [11] and other nonlinear models [7]. Despite that, the accuracy of these models is questionable, especially when dealing with a highly uncertain energy source such as the Sun. Moreover, such models do not take into consideration system's losses. Thus, accurate and powerful modeling techniques must be employed to accurately model the PV array. On the other hand, the battery models that are being used in sizing a standalone PV system can be classified into two categories; simple [4] and complex battery models [30]. The simple battery model can be defined as a series of equations that express the status of the battery without reflecting the dynamic behavior of the battery's charging and discharging processes. Such a model may cause an inaccurate sizing result as the battery's state of charge is not calculated accurately. On the other hand, in complex battery model, the dynamic behavior of the battery charging and discharging process are considered [31]. As for the simulation method, currently there are many simulation methods for standalone PV system sizing methods. As mentioned before a simulation algorithm for sizing standalone PV system must handle the input data, generate a design space and evaluate each candidate in the generated design space based on a specific criterion. In the early stage of this science, simple iterative algorithms were utilized to conduct such a task as the handled data were few (monthly averages, for example) [18]. In the meanwhile, handling hourly data makes such algorithms unable to converge or the execution time becomes very long. Therefore some of the authors utilized artificial intelligence (AI) based approaches such as genetic algorithm (GA), particle swarm optimization (PSO), harmony search (HS), and biogeography based optimization (BBO) [32]. These searching algorithms, overcome the drawback of the iterative algorithms as they are able to generate a design space in a random way with much faster process. In addition to that, some of authors combined some of the AI techniques with iterative methods whereas, optimization results are obtained by the iterative algorithm first, then prediction models such as artificial neural networks (ANNs) are utilized to predict these results for future uses.

Based on the reviewed literature, a good size optimization algorithm must handle small step meteorological and load demand time series data (hourly or smaller), implies accurate system's models, utilizes a well formulated objective function and have a fast and accurate simulation algorithm. Thus, in this paper, an improved numerical method is proposed to optimally size a standalone PV system. The improvements done in this paper are presented into three parts. Firstly, a novel technique for modeling the output PV array current in a standalone PV system using Random Forest (RFs) is proposed. In addition to that, a dynamic battery model is utilized which reflect the dynamic behavior of the storage battery. Moreover, the proposed sizing algorithm is designed in order to be converges faster than the iterative algorithm that is proposed in Ref. [33]. Finally, experimental data of a 3 kWp PV system installed at the Universiti Kebangsaan Malaysia campus are used for this purpose. These data contain hourly solar radiation, ambient temperature, number of solar day, number of hours per day, number of PV modules and actual system output current.

## 2. Modeling of standalone PV system

Standalone PV system is consisted of a PV array, storage battery, DC to DC converter, DC to AC inverter, and a load which can be AC and/or DC. The PV array is the main energy source in the system while the battery bank stores energy when the power supplied by the PV arrays exceeds the load demand and it releases energy backs when the energy produced by PV is insufficient. Finally the power conditioning unit provides an interface between all the components of the PV system, giving protection and control [34].

### 2.1. Modeling of PV array

The hourly output of the PV array is mainly depending on solar radiation, and solar cell temperature. The changing of solar radiation affects the output current produced by a PV array proportionally. On the other hand, the ambient temperature negatively affects the PV array output voltage proportionally. In the meanwhile, increasing the solar radiation that gained by the PV array increases the PV array output current in a proportional relation and vice versa. However, increasing the ambient temperature reduces the output voltage of the PV array in a proportional relation and vice versa. The output current of PV array ($I_{PV}(t)$) can be described empirically as follows,

$$I_{PV}(t) = n_p I_M \left(\frac{G(t)}{G_{STC}}\right) + \left(1 + \alpha\left(T_c(t) - T_{c,\,STC}\right)\right), \tag{1}$$

Where $n_p$ is the number of PV modules in parallel, $I_M$ is the current of PV module, $G_{STC}$ is the solar radiation under STC, $G(t)$ is the instantaneous solar radiation, $\alpha$ is the short-circuit temperature coefficient, and $T_{c,STC}$ is the cell temperature at STC. The temperature ($T_c(t)$) in Eq. (1) is the cell temperature and it can be obtained by,

$$T_c(t) = T_{amb} + \left(\frac{NOCT - 20}{800}\right) G(t) \tag{2}$$

where *NOCT* is the nominal operating cell temperature which is usually supplied by the manufacturer. *NOCT* is defined as the operating temperature of a PV module which is measured under